THE DEVELOPMENT AND CONSTRUCTION OF A VACUUM-TUBE VOLTMETER OF HIGH ACCURACY

A THESIS
Submitted in partial fulfillment
of the requirements for the Degree
of Master of Science in Electrical Engineering

by

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1940

NTZ Sept '48

APPROVED

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THE DEVELOPMENT AND CONSTRUCTION OF A VACUUM-TUBE VOLTMETER OF HIGH ACCURACY

INTRODUCTION

The present rapid technical progress in television, frequency modulation, and other electronic applications requires that the communications engineer have measuring instruments of high accuracy and of great flexibility. The most urgent need is for a voltmeter capable of accurately measuring both direct-current and high-frequency alternating-current potentials across high-impedance circuits.

Thermionic voltmeters capable of making these measurements are commercially available. Those in the lower price bracket, however, are of doubtful accuracy, while most of the thermionic voltmeters on the market are limited in the types of measurements they can make. The accuracy of all of these voltmeters is dependent primarily upon the accuracy of the calibration of a d'Arsonval type direct-current milliammeter over its entire scale.

Only the slide-back and degenerative types of voltmeters are reasonably independent of the constants of the tube and variations, or drifts, in power supply voltages. Slide-back vacuum-tube voltmeters possess an inherent advantage over all other types in that they are self-calibrating: the voltage reading is read from a linearly calibrated direct-current voltmeter. The overall accuracy is limited by the accuracy of this voltmeter. Alternating-current slide-back triode and tetrode voltmeters are subject to an error of setting which varies with the magnitude of the input voltage. Direct-current slide-back triode and tetrode voltmeters are precise instruments, yet they possess the two main disadvantages of all slide-back voltmeters: they are not direct-reading, and they employ a sensitive microammeter, which can be easily injured, as a balance indicator.

The grid-detection and the plate-detection types of thermionic voltmeters must be frequently calibrated, since changes in the characteristics of the tube employed seriously affect the calibration. It is possible to construct these voltmeters so that there is automatic compensation for supply voltage variation. The square-law voltmeter can measure only small voltages directly, as vacuum-tubes have an approximate square-law characteristic over only a small range. The magnitude of voltages which can be accurately measured with class "B" voltmeters is determined by the cut-off value of bias for the particular tube employed.

Highly degenerative thermionic voltmeters have a sensitivity almost completely independent of the constants of the tube and of moderate variations in supply voltages. Reasonably high voltages are readily measured with degenerative voltmeters employing a large value of feed-back resistance in the cathode lead by increasing simultaneously the value of this resistance and the plate supply voltage. The meter reading of the direct-current degenerative thermionic voltmeter is almost directly proportional to the voltage introduced into the grid circuit over a wide range of voltages. For precise measurements, the meter scale is directly calibrated, or a calibration curve is plotted.

A careful consideration of the advantages and of the disadvantages of various vacuum-tube voltmeter circuits indicates that the most flexible circuit for a universal a-c d-c voltmeter to be used for voltage measurements of from 0.1 to 150 volts is a direct-current thermionic voltmeter used with a linear diode peak rectifier for alternating-current measurements. The convenience and the high accuracy of this particular combination is shown in the material which follows.

The voltmeter should fulfill the following desirable conditions:

(1) The absolute calibration should be dependent upon a minimum of known, and readily measurable, circuit parameters.

(2) The absolute calibration should be completely independent of the constants of the vacuum-tube.

(3) The absolute calibration should be independent of permanent changes in battery supply potentials.

(4) The direct-current voltmeter should be capable of measuring the voltage across a charged condenser, that is, its direct-current input resistance should be extremely high.

(5) The input radio-frequency resistance should be on the order of megohms up to moderately high frequencies.

(6) The input capacitance should not exceed 5 to 10 micromicrofarads, while the resonant frequency of the input circuit should be 100 megacycles or higher.

(7) The voltmeter should be self-calibrating.

(8) The voltmeter should be self-protected against reasonable overloads.

(9) The voltmeter should have a direct reading feature.

THE DIRECT-CURRENT VACUUM-TUBE VOLTMETER

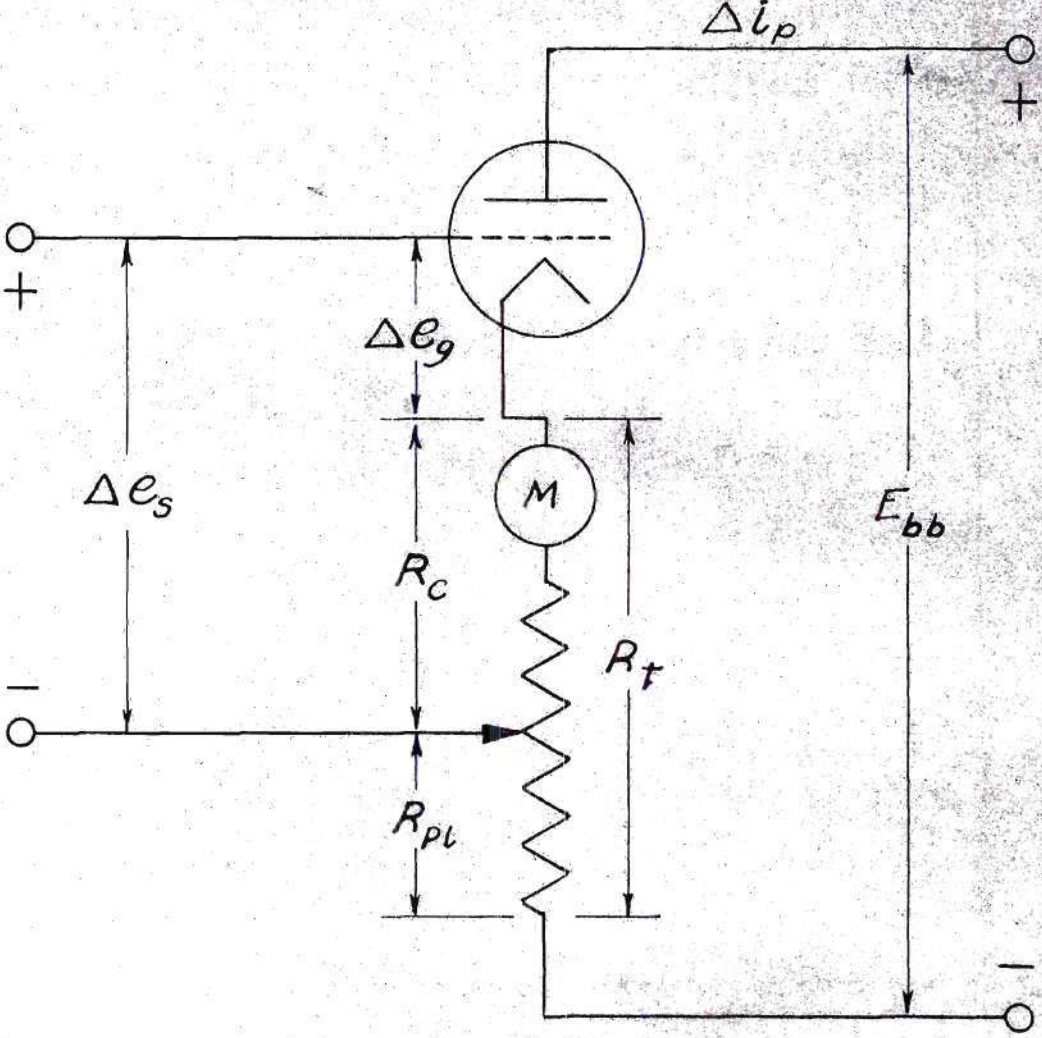
THEORY OF THE SLIDE-BACK VOLTMETER

The direct-current vacuum-tube voltmeter employs a circuit developed by the writer. It is a degenerative slide-back triode voltmeter especially designed to incorporate the advantages of both the slide-back and the degenerative voltmeters and at the same time to minimize most of their undesirable characteristics. One of the features of this voltmeter is that it embodies an accurate calibrating standard as an integral part and that it uses a single meter for the balance indication and the voltage reading.

Figure 1 is the fundamental circuit of the voltmeter. Initially the potentiometer is adjusted so that with the input terminals either shorted, or connected to a high resistance, the plate current is exactly one milliampere. The unknown voltage is then connected to the input terminals and the potentiometer readjusted until the plate current is again exactly one milliampere. The increase in the resistance of R_c in kilo-ohms will then be the value of the unknown voltage.

It is apparent that, in a self-biasing arrangement of this type, the grid is always negative with respect to the cathode at the reference balance condition. Under this operating condition, there can be only a minute grid current due to insulation leakage and positive gas ions in the tube;

Fig. 1



Fundamental Circuit of Slide-back Voltmeter

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so that the input resistance of the tube is extremely high. The flow of an appreciable grid current would only reduce the input resistance without affecting the calibration of the voltmeter, for it is the product of the total current flowing through R_c, as read on the meter M, and the value of the resistance of R_c which determines the reading. Therefore, the voltmeter would still indicate the true voltage across its input terminals.

Wide changes in the plate potential have no effect on the accuracy of the voltmeter so long as the plate potential remains constant during the interval between the initial and final adjustments of the potentiometer: it is necessary only to have a plate potential high enough so that the plate current may be adjusted to the nominal reference value of one milliampere.

Vacuum tubes with far different characteristics may be interchanged in the voltmeter without affecting the calibration. Here again it is only necessary that the particular tube employed may be adjusted to draw the nominal value of plate current.

The calibration and the accuracy of the voltmeter is solely dependent upon the calibration of the potentiometer in ohms, and the calibration of one single point on the milliammeter. The sensitivity of adjustment of the plate current to the nominal value depends upon the design of the circuit. The range of input voltages which can be measured is governed by the total resistance of the potentiometer and the voltage of the plate supply.

The effect of the various circuit parameters on the operation of the voltmeter may be determined to a first approximation through a mathematical investigation of the circuit by use of the equivalent plate circuit theorem. In this analysis, an incremental change in grid voltage, Δe_g, acting from the grid to the cathode is replaced by an equivalent voltage $u\Delta e_g$ acting in the plate circuit.

Referring to Fig. 1, the voltage Δe_g acting on the grid circuit causes an incremental change in plate current:

$$\Delta i_p = \frac{u \Delta e_g}{r_p + R_t} \qquad (1)$$

where u is the amplification factor and r_p is the dynamic plate resistance of the tube. R_t is the total resistance in the external plate to cathode circuit.

For any particular setting of the potentiometer,

$$R_t = R_{p1} + R_c \qquad (2)$$

The change in plate current Δi_p flowing through R_c produces the voltage drop $\Delta i_p R_c$ with a polarity opposite to Δe_s, the incremental change in input signal voltage. The actual incremental grid voltage acting from the grid to the cathode of the tube is, therefore, defined by the equation,

$$\Delta e_g = \Delta e_s - \Delta i_p R_c \qquad (3)$$

Substituting equation (3) in equation (1):

$$\Delta i_p = \frac{u\,(\Delta e_s - \Delta i_p R_c)}{r_p + R_t}$$

Solving for Δi_p:

$$\Delta i_p\,(r_p + R_t) = u\Delta e_s - u\Delta i_p R_c$$

$$\Delta i_p\,(r_p + R_t + uR_c) = u\Delta e_s$$

$$\Delta i_p = \frac{u\Delta e_s}{r_p + R_t + uR_c}$$

Dividing the numerator and the denominator of the right-hand term by u:

$$\Delta i_p = \frac{\Delta e_s}{\left\{\frac{r_p + R_t}{u}\right\} + R_c} \qquad (4a)$$

For large values of R_t or of R_c

$$\Delta i_p \approx \frac{\Delta e_s}{K + R_c} \qquad (4b)$$

<u>6F5GT Characteristics at Nominal Operating Point</u>

Amplification Factor	100
Plate Resistance	61,000 ohms
Mutual Conductance	1,640 micromhos

Over a reasonably large range of operation, it can be assumed with a good degree of accuracy that the term in the brackets is a constant. Both u and r_p remain constant when the point of operation is in the vicinity of the nominal plate current. (See Fig. 2) Under this condition, equation (4a) accurately gives the incremental change in plate current.

For a given incremental change in input signal voltage, the change in plate current approaches a maximum as R_c approaches zero. (R_c can be made zero only if a "C" battery is employed to bias the tube to the nominal operating point.) As R_c is increased, the least perceptible change in i_p is decreased, and with it the sensitivity of adjustment is decreased. However, R_c is small when low voltages are measured, and large only when high voltages are measured; so that the percentage of accuracy of the setting remains reasonably constant over the entire operating range of the voltmeter.

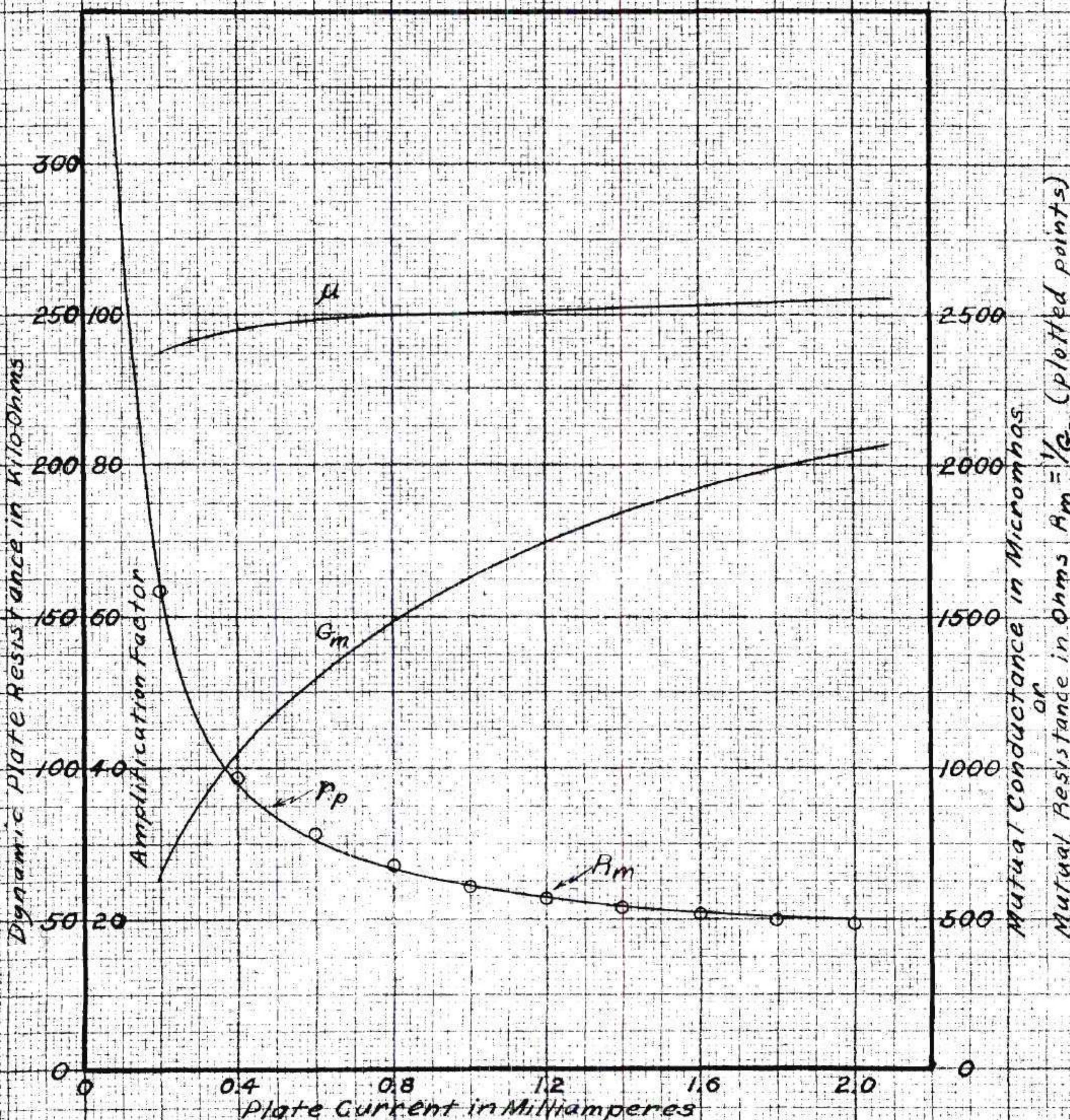
An examination of equation (4) shows further that the sensitivity of the voltmeter increases with a decrease in R_t to the minimum permissible value for the particular input voltage measured. It is very desirable to employ a tube with a high amplification factor and a high mutual conductance so as to make the term in the brackets a minimum.

Fig. 2

6F5GT Characteristics

Values obtained at intersections of 101,000 ohm load-line with family of $i_b - e_b$ characteristics

Plate Supply voltage = 250 volts
Heater Voltage = 5.3 volts
External Plate circuit res. = 101,000 ohms
Nominal Plate Current = 1 ma.



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THEORY OF THE DEGENERATIVE VOLTMETER

By rearranging the circuit of Fig. 1 so that the zero-signal plate current may be balanced out of the meter circuit, the voltmeter becomes a direct-reading degenerative vacuum-tube voltmeter. The fundamental circuit arrangement is shown in Fig. 3.

The zero-balance equation for the milliammeter is:

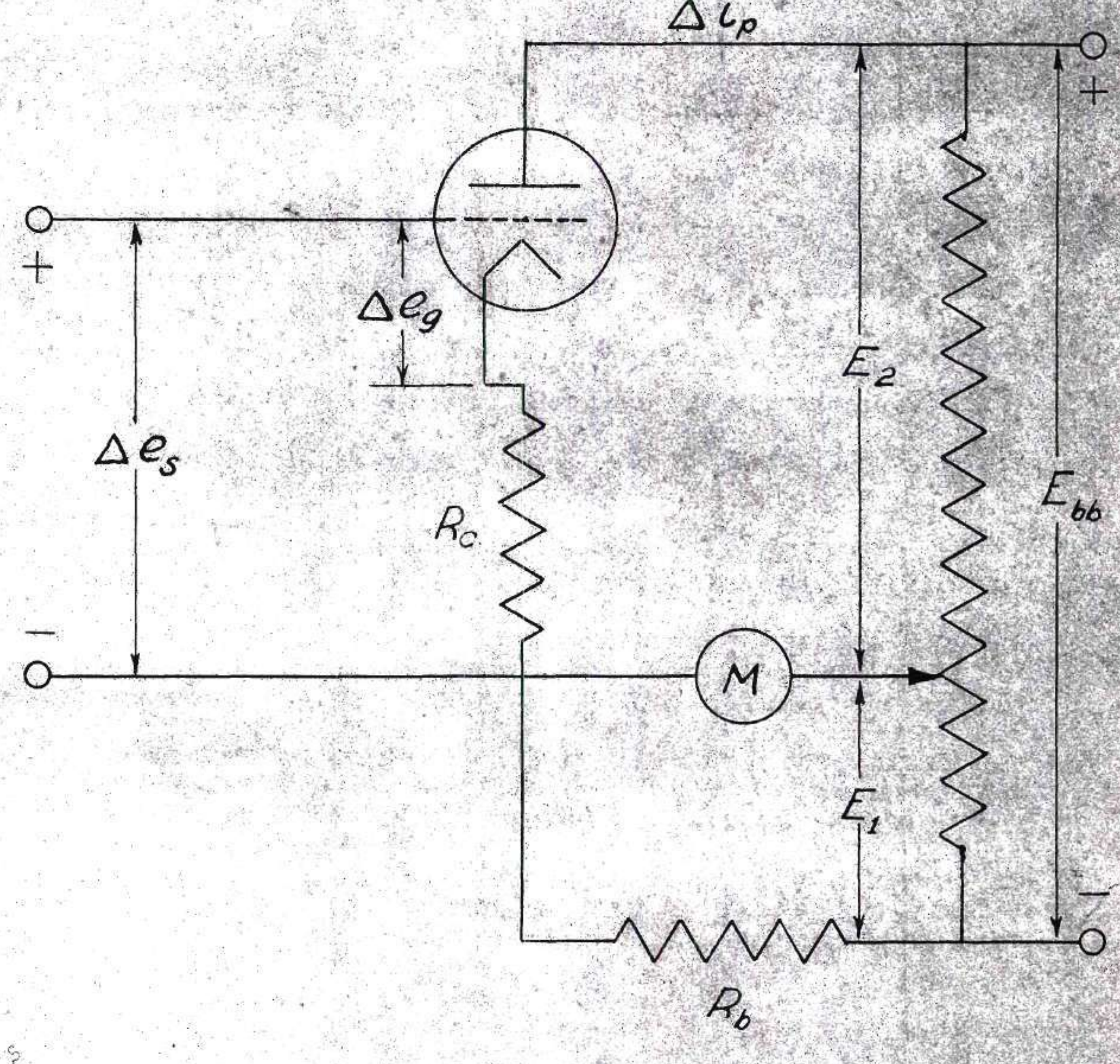
$$\frac{R_b}{R_c + R_p} = \frac{E_1}{E_2} \qquad (5)$$

where R_p is the static plate resistance of the tube. When this equation is satisfied, the direct current through the meter is zero. The balance resistor R_b should be high enough so that it will not reduce the sensitivity of the meter excessively. If R_b is increased, E_1 must be increased to satisfy the balance equation. Variations in the plate supply potential have little effect on this balance.

Using the notation of Fig. 3 and the same method used to derive Eq. 4, the dynamic equation for the plate current is:

$$\Delta i_p = \frac{u \Delta e_s}{r_p + (u + 1) R_c} = \frac{\Delta e_s}{\frac{1}{G_m} + (\frac{u + 1}{u}) R_c} \qquad (6a)$$

Fig. 3



Fundamental Circuit of Degenerative Voltmeter

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If a high-mu tube is employed, Eq. 6a reduces to

$$\Delta i_p \approx \frac{\Delta e_s}{R_m + R_c} \qquad (6b)$$

where R_m is in the nature of a resistance, which may be called the mutual, or transfer, resistance of the tube. The manner in which R_m varies with the plate current for a high-mu triode is shown in Fig. 2. If there is to be a linear relationship between the input voltage and the plate current, R_c must be many times as large as R_m. However, as R_c is increased in value, the sensitivity of the circuit to small direct voltages is correspondingly decreased. For the measurement of high direct voltages, R_c is made large, and a linear characteristic is readily realized.

By arbitrarily setting R_c at different values, the voltmeter will give a full-scale reading on any desired voltage within the range of the voltmeter. The scale of the milliammeter need not be calibrated directly in volts, since any voltages read may always be checked exactly by shifting to the slide-back connection. In other words, the degenerative direct-reading voltmeter is readily calibrated against the slide-back voltmeter.

TABLE I

6F5GT RATING AND CHARACTERISTICS

	Average Rating	Values Used
Heater Voltage	6.3 volts	5.3 volts
Plate Voltage	250 volts	150 volts
Grid Voltage	- 2 volts	- 1.07 volts
Plate Current	0.9 ma.	1.0 ma.
Amplification Factor	100	100
Plate Resistance	66,000 ohms	61,000 ohms
Mutual Conductance	1,500 umhos	1,640 umhos
Grid-Plate Capacitance	2.3 uuf.	
Grid-Cathode Capacitance	2.2 uuf.	
Plate-Cathode Capacitance	2.9 uuf.	

RCA-955 TRIODE RATINGS AND CHARACTERISTICS

Heater Voltage	6.3 volts
Heater Current	0.15 amperes
Plate Voltage	90 volts
Grid Voltage	- 2.5 volts
Plate Current	2.5 ma.
Plate Resistance	14,700 ohms
Amplification Factor	25
Mutual Conductance	1,700 umhos
Grid-Plate Capacitance	1.4 uuf.
Grid-Cathode Capacitance	1.0 uuf.
Plate-Cathode Capacitance	0.6 uuf.

THE DESIGN OF THE SLIDE-BACK VOLTMETER

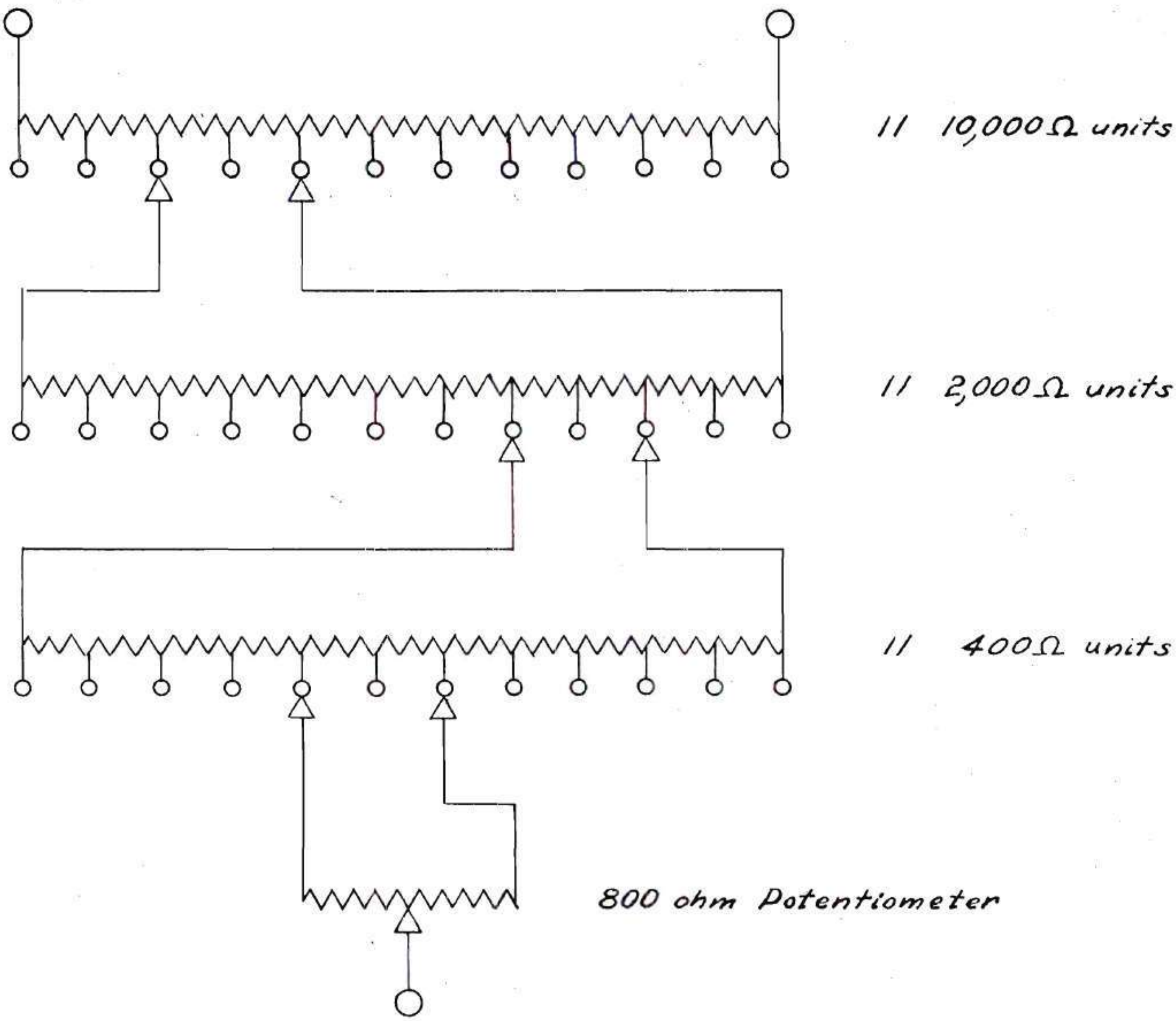
The tube employed in the voltmeter is a 6F5GT, a high-mu triode with a small glass envelope. Its measured characteristics are given in Table I. This tube was chosen for its high amplification factor and its normal plate current of 0.9 milliampere, which is close to the nominal desired value of 1 milliampere. With this small value of plate current, the potentiometer will be called upon to dissipate very little heat, and the resistors comprising the potentiometer will remain constant in value even after extended periods of operation.

The grid lead of the 6F5GT is brought through the top of the glass envelope, thus insuring an extremely high resistance path between the grid and the other elements in the tube. One of the characteristics of this tube is its low gas content and low ionic current. The heater is operated at approximately 85% of its normal value of 6.3 volts in order to insure that the grid current be as small as possible, since the active cathode emitting material is often accidentally sprayed on the grid wires and there is danger that the grid might emit electrons.

The potentiometer may be of the wire-wound variety, since the residuals, the inductance and the distributed capacitance of the resistance, do not affect the direct-current resistance of the potentiometer.

A detailed diagram of the potentiometer is given in Fig. 4.

Fig. 4



100,000 ohm Thomson-Varley Potentiometer

11 units of R ohms each

11 units of $R/5$ ohms each

11 units of $R/5^2$ ohms each

1 potentiometer of $10\,R/5^3$ ohms

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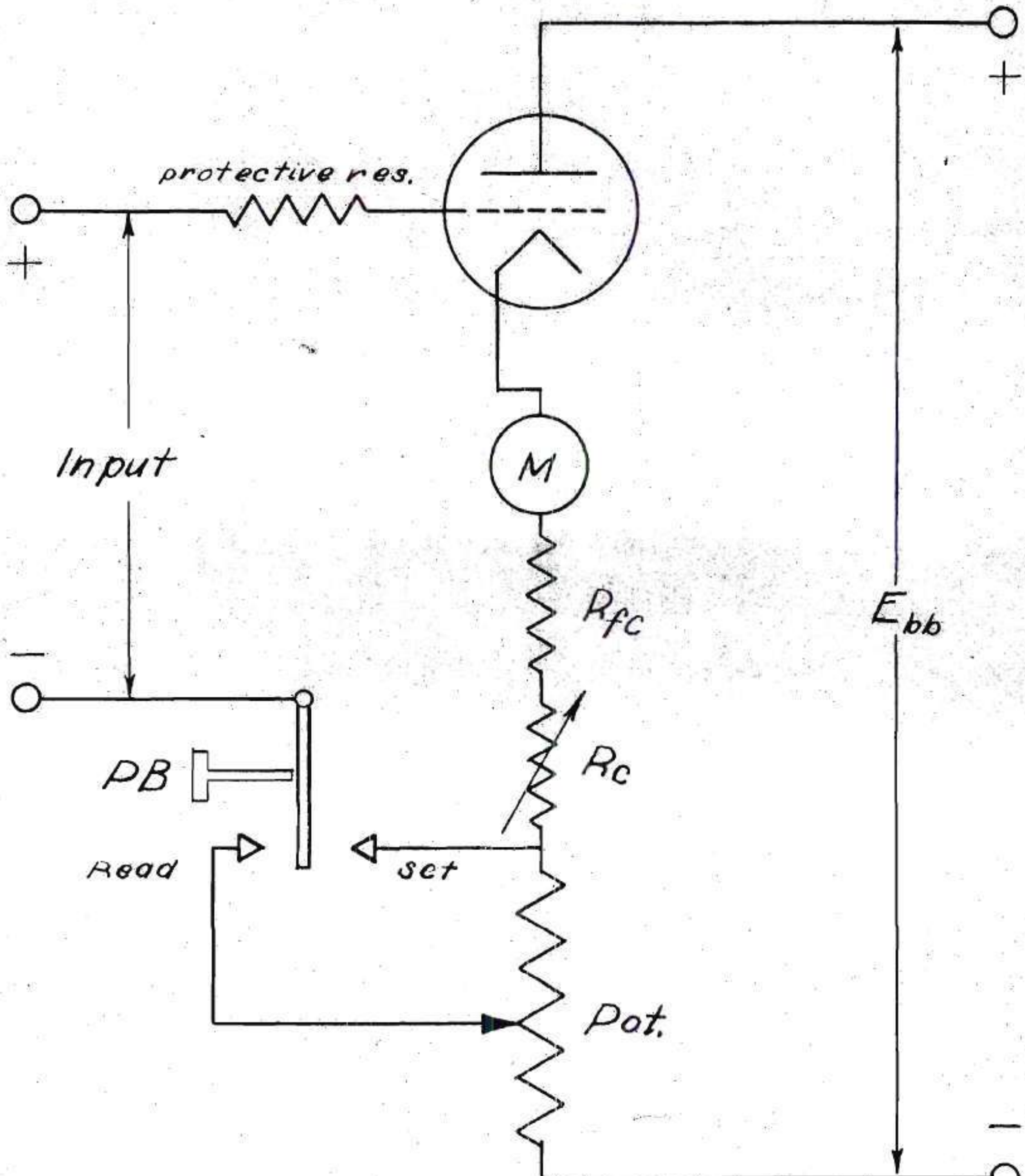
It is a four-dial potentiometer of the Thomson-Varley type. The first dial consists of eleven 10,000 ohm resistors, the second consists of eleven 2,000 ohm resistors, and the third consists of eleven 400 ohm resistors. These resistor units have an accuracy of 1/10 of 1%. They are non-inductively wound on a grooved ceramic form and have a safe power dissipation rating of one watt. The last dial consists of 1,000 ohm wire-wound potentiometer connected in parallel with a 4,000 ohm wire-wound fixed resistance; thus the combination is an 800 ohm potentiometer. A twenty-step potentiometer consisting of twenty 40 ohm wire-wound resistors of 1/10 of 1% accuracy would be more accurate than the wire-wound potentiometer. However, the accuracy of the wire-wound potentiometer is considered adequate for the fourth significant figure.

The switches employed in the potentiometer are of the two-gang, eleven-position type with silvered contacts. The contact resistance of this type switch is negligible as compared to the value of the resistors comprising the potentiometer.

As the normal current flowing through the potentiometer is only one milliampere, the temperature rise, and hence the change in resistance of the potentiometer, after extended periods of operation, is negligible. All of the resistors are located in a compartment separate from all of the heat generating equipment such as the tubes, the transformer, and

Fig. 5



Practical Circuit of Slide-back Voltmeter

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the bleeder resistance.

The meter employed is a five-inch diameter, front-of-panel mounting 0-1.5 milliammeter of the d'Arsonval type. The meter face is calibrated with 0-15 and 0-150 volt linear scales, and has a mirrored face to eliminate parallax. The one-milliampere point was accurately set by comparison with three milliammeters of the precision type. Two terminals are provided on the panel of the vacuum-tube voltmeter so that an external milliammeter may be readily connected in series with this milliammeter for calibration purposes. The insertion of an external milliammeter in the circuit of the vacuum-tube voltmeter does not affect the calibration of the voltmeter in any way. An expensive meter need not, therefore, be incorporated in the voltmeter, as an accurate laboratory milliammeter can conveniently be employed with the vacuum-tube voltmeter for precision readings.

In order to reduce to a minimum the manual operations which must be performed in making a voltage reading, the basic circuit of Fig. I was rearranged as in Fig. 5. With the input terminals of the voltmeter either shorted or connected to a d-c path, the push-button PB is pressed and R_c is adjusted so that the meter M reads exactly one milliampere. Then the push-button is released and the voltmeter is ready for use. The fixed resistance R_{fc} acts as a protective degenerative resistance and insures that there always be some bias on the tube regardless of the setting of R_c.

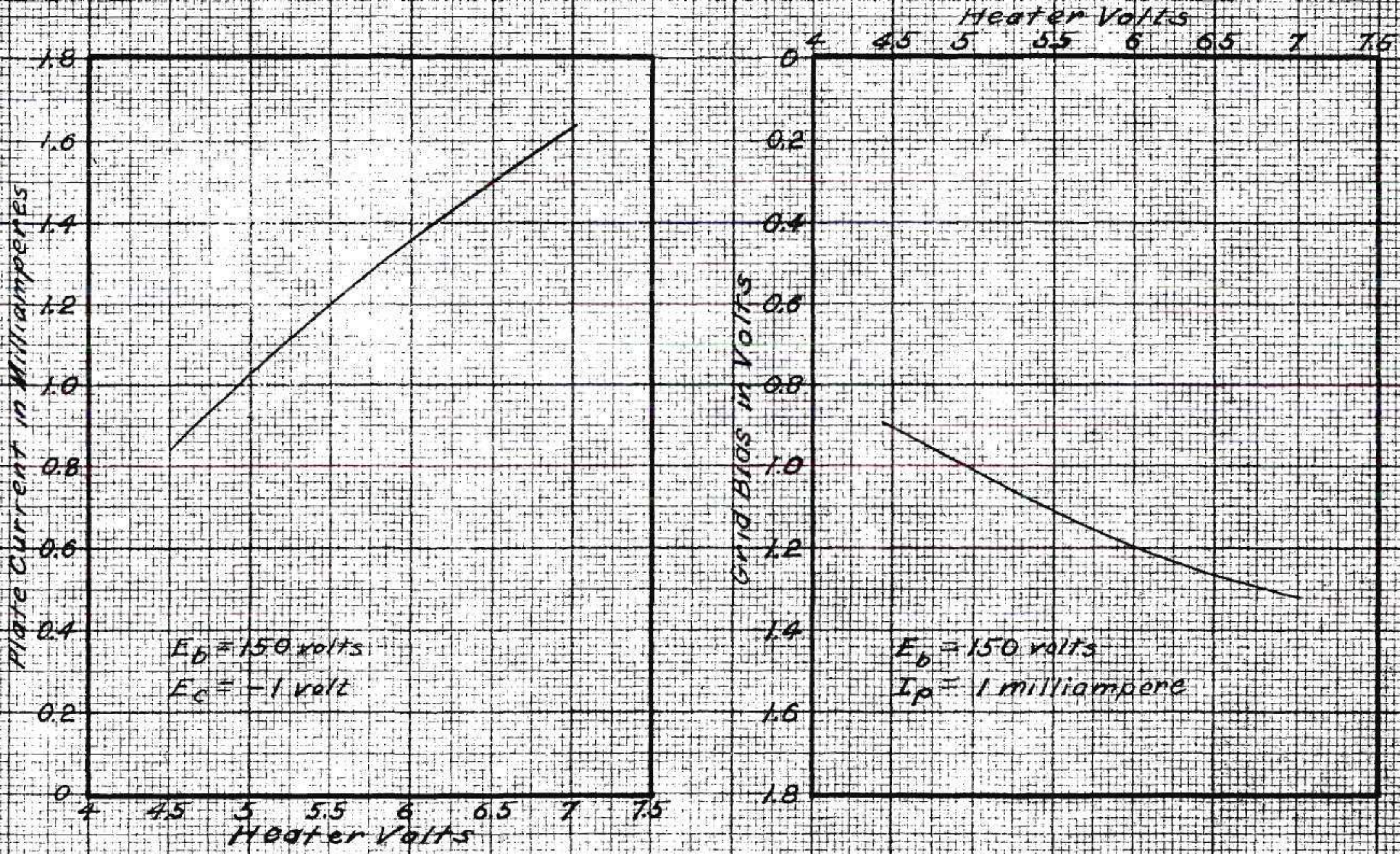
An examination of Fig. 6 shows that with a plus or minus

Fig 6

6F5GT Characteristics

Showing the effect of changes in heater voltage on the operating characteristics

Nominal Heater Voltage = 5.3 volts



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10% variation in filament voltage the grid bias must be capable of adjustment within the limits of -0.95 and -1.15 volts in order to maintain the plate current at one milliampere with 150 volts from plate to cathode. It is evident that R_c must be capable of adjusting the bias within these limits. However, in order to compensate for tubes with different characteristics, R_{fc} is 750 ohms and R_c is 1,000 ohms, thus permitting bias adjustments of from -0.75 to -1.75 volts. This wide range of bias adjustment also permits R_c to compensate for the stray voltage developed across a diode when making alternating current measurements.

Fig. 7 shows that if the grid becomes positive on overload, the plate current cannot exceed 2.475 milliamperes. However, under such a condition, grid current flows, and the meter will read the sum of the plate and the grid currents. The meter is not seriously overloaded since the grid current flowing through R_c tends to decrease the grid potential. If the normal grid current with the grid at a negative potential is negligible, the meter may be placed directly in the plate circuit. In either case, there is little danger of overloading the milliammeter even though the input voltage is excessively high, since the one megohm resistance in series with the grid limits the grid current.

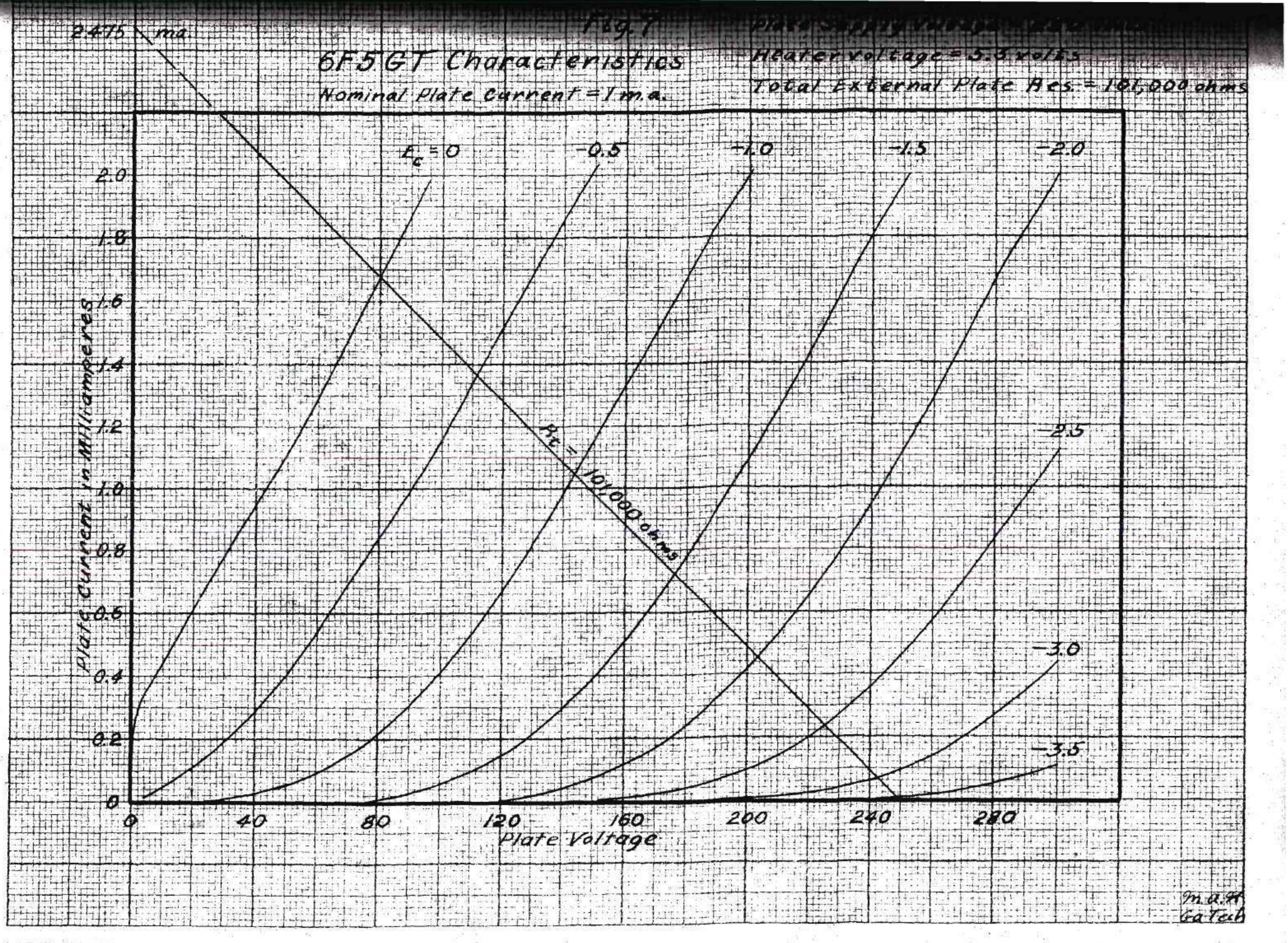
Fig. 7
6F5GT Characteristics
Nominal Plate Current = 1 m.a.
Heater voltage = 5.3 volts
Total External Plate Res. = 101,000 ohms
2.475 ma
E_c = 0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
R_L = 101,000 ohms
Plate Current in Milliamperes
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
40
80
120
160
200
240
280
Plate Voltage
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THE POWER SUPPLY

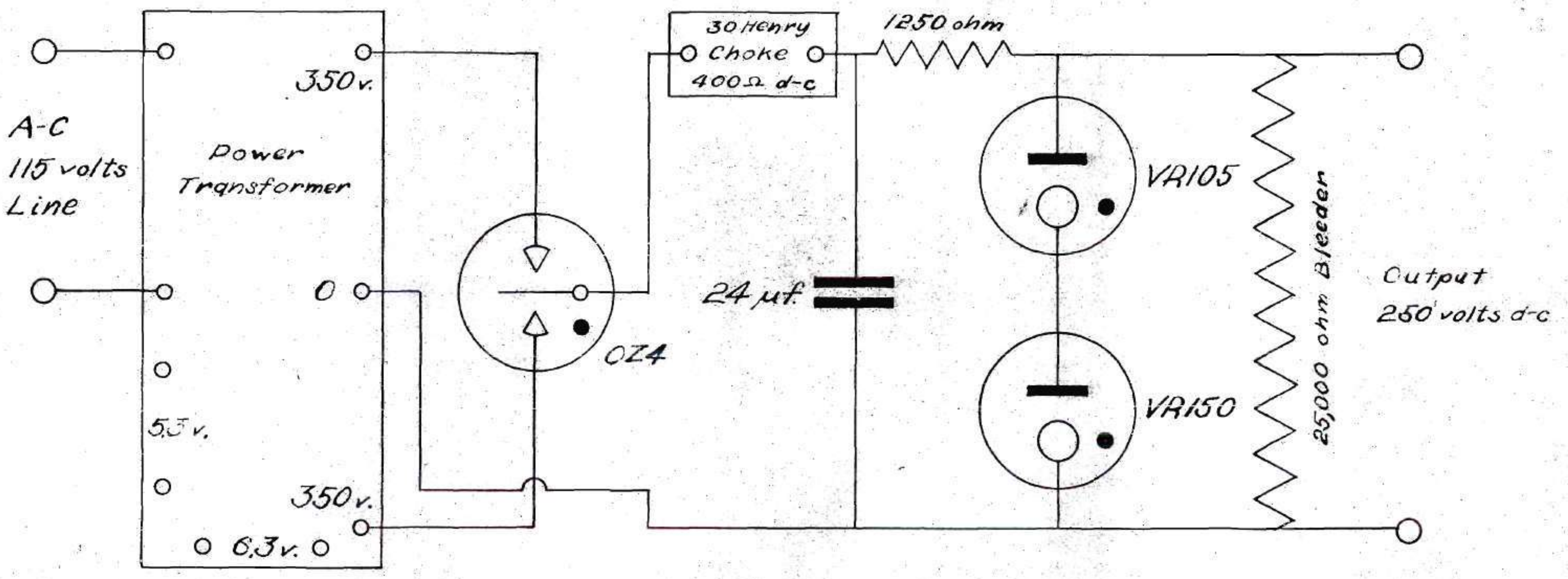
One of the prime requisites of an a-c power supply to be used with a vacuum-tube voltmeter is that its output voltage remain constant and be fixed at a definite value with wide variations in the a-c input line voltage. Since the voltmeter requires a current of only 2 milliamperes at 250 volts, a small power supply suffices.

The diagram of the power supply is shown in Fig. 8. The rectifier, an OZ4, is a cold-cathode, full-wave, arc-discharge tube, which was selected because of its high efficiency and small physical size. The OZ4 has a definite negative-resistance characteristic illustrated in Fig. 9. The voltage drop through the tube decreases as the current through the tube increases. This decrease in voltage drop will tend to compensate for voltage drops in the filter choke and in the power transformer.

The filter consists of a low-pass L-section composed of a 30 henry choke coil, and a 24 microfarad electrolytic condenser. This filter is adequate, as the voltage regulator provides additional filtering.

Several voltage regulators employing a triode regulator tube were tried. Fair results were obtained when a "C" battery was used to maintain a definite bias on the grid, but the use of a battery in a voltage regulator was deemed undesirable. A triode voltage regulator used with a small neon tube proved unsatisfactory due to the fact that the neon tube

Fig. 8



Voltage Regulated Power Supply

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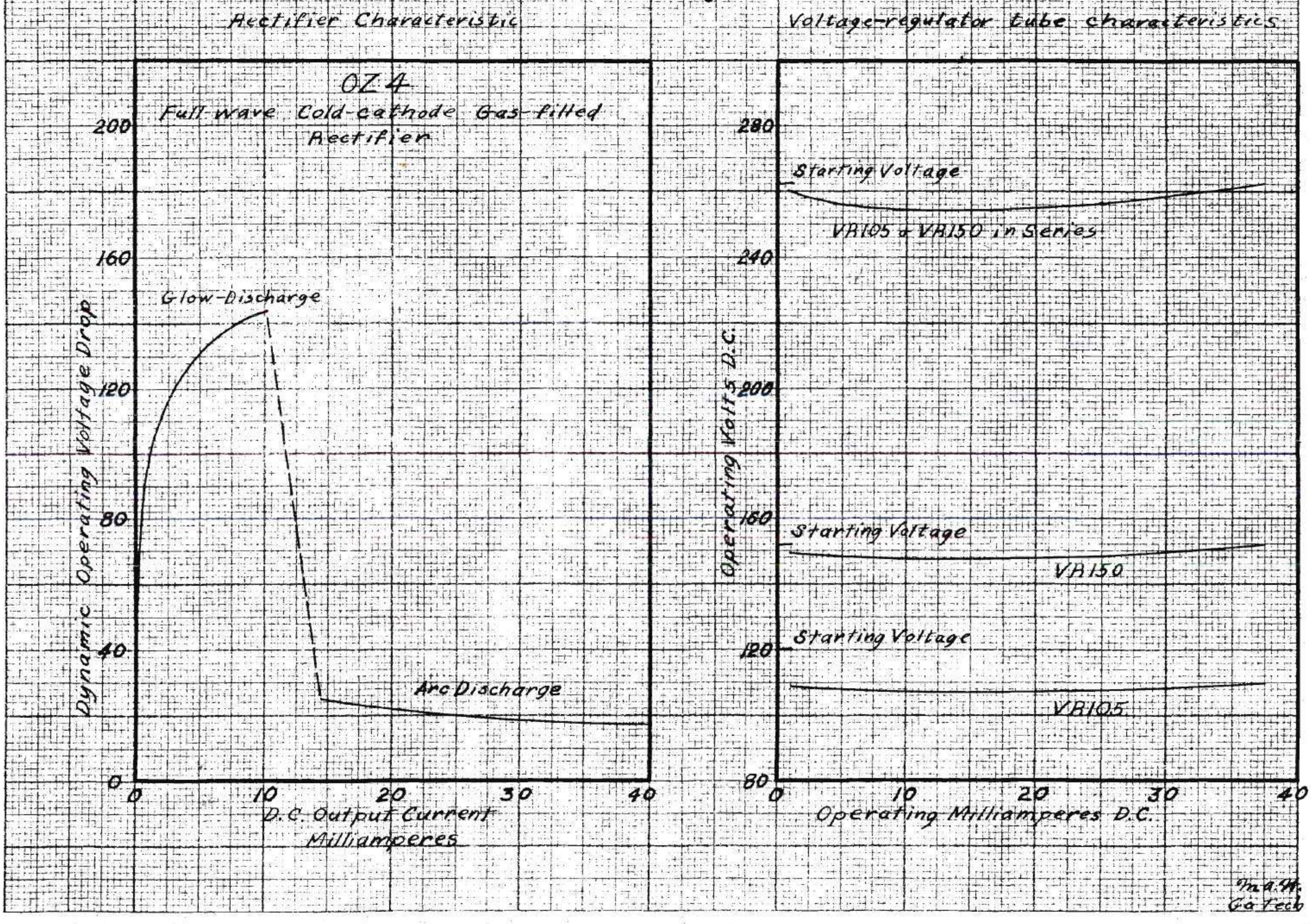
had a rising voltage-current characteristic. Even though the circuit was designed to compensate for this positive-resistance characteristic of the neon tube, it was impossible to compensate in any simple manner for the change in the mutual conductance of the regulating triode when its filament voltage changed with changes in the a-c line voltage.

The most satisfactory voltage regulator tested proved to be the simplest arrangement; so it was adopted for use in the voltmeter. It consists of two glow discharge tubes connected in series to give the desired 250 volts. The individual current-voltage characteristics and the total characteristic of these tubes, a VR105 and a VR150, are shown in Fig. 9. (See Table II for the characteristics of these tubes.) The circuit constants were chosen so that 20 milliamperes flow through the regulator tubes and 10 milliamperes flow through the bleeder resistance. With a total minimum current of 30 milliamperes, the operation of the OZ4 is quite stable.

The total heat dissipation of the power supply and voltage regulator including the rectifier tube and the bleeder resistance is about 10 watts. It is well to point out that the power dissipation of the filament alone in an 80 type rectifier tube is 10 watts. This factor is very important, as cumulative heating in any precision instrument tends to change the value of such circuit components as resistances, inductances and condensers, as well as to reduce the insulating quality of such insulators as glass, paper and rubber.

Fig. 9



Rectifier Characteristic
OZ4
Full-wave Cold-cathode Gas-filled Rectifier
Glow-Discharge
Arc Discharge
Dynamic Operating Voltage Drop
D.C. Output Current Milliamperes
0
40
80
120
160
200
10
20
30
Voltage-regulator tube characteristics
Starting Voltage
VR105 & VR150 in Series
Starting Voltage
VR150
Starting Voltage
VR105
Operating Volts D.C.
Operating Milliamperes D.C.
80
120
160
200
240
280
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Fig. 6 shows the manner in which the plate current of the 6F5GT varies with a change in heater voltage, when the plate voltage and the grid bias are held constant. Since the heater of this tube has enough thermal inertia to eliminate fluctuations of plate current due to rapid variations of heater voltage, it was considered unnecessary to employ a voltage regulator to keep the heater voltage constant.

The power supply is in a shielded compartment which is provided with several ventilating holes carefully placed to insure adequate cooling of the heat-generating equipment, regardless of the position in which the voltmeter is placed.

TABLE II

OZ4 RATINGS AND CHARACTERISTICS

Ionic Heated Cathode	
Maximum D-C Output Voltage	300 volts
Minimum D-C Output Current	30 ma.
Maximum D-C Output Current	75 ma.
Maximum Peak Plate Current	200 ma.
Minimum Starting Peak Voltage	300 volts
Average Dynamic Voltage Drop	24 volts

TENTATIVE RATINGS OF VOLTAGE REGULATOR TUBES

	VR105	VR150
D-C Starting Voltage (Min.)	137	180 volts
D-C Operating Voltage (Approx.)	105	150 volts
D-C Operating Current (Min.)	5	5 ma.
D-C Operating Current (Max.)	30	30 ma.

THE DIODE VOLTMETER

THEORY

The utility of a diode rectifier of small dimensions as a peak voltmeter for the measurement of radio-frequency voltages is well recognized. L. S. Nergaard and W. R. Ferris of R. C. A. have shown that the input resistance of a diode at the ultra-high frequencies is higher than that of a triode of equivalent physical size. The input capacitance of a diode voltmeter can, by proper circuit arrangement, be kept at a definite low value.

The selection of an RCA-955 tube with the grid and plate tied together to form a diode is based on the work of L. S. Nergaard, who has pointed out that there are two major sources of error in the reading of a diode voltmeter at the ultra-high frequencies:

(1) A resonance error due to series resonance between the lead inductance and the inter-electrode capacitance, which causes the diode voltmeter to read high.

(2) "Premature cut-off" due to the appreciable transit time of electrons from the cathode to the anode, which causes the diode voltmeter to read low.

Both of these errors can be kept down to a low value by using diodes of small physical dimensions. The resonance error is the greater of the two errors.

The series resonant wavelength of the RCA-955 with grid and plate tied together is about 40 centimeters. It has a resonance error of approximately plus 16% at 100 centimeters wavelength and 64% at 50 centimeters. The series resonance and transit time correction formulas for the 955 as determined by Nergaard are:

Correction formula for resonance error,

$$\frac{E_1}{E_2} = \frac{1}{1 - \omega^2 L_d C_d}$$

Therefore,

$$E_2 = E_1\left[1 - \left(\frac{\lambda_r}{\lambda}\right)^2\right]$$

For the RCA-955,

$$E_2 \approx E_1\left[1 - \left(\frac{40}{\lambda}\right)^2\right] \qquad (7)$$

Where

L_d = inductance of diode leads

C_d = inter-electrode capacity of the diode

λ_r = resonant wavelength of diode in centimeters

λ = operating wavelength in centimeters

E_2 = voltage across diode terminals

E_1 = voltage across diode electrodes

This formula holds only if the operating wavelength is sufficiently higher than the resonant wavelength so that the lead resistance may be neglected.

Correction formula for transit time error for the 955 is,

$$\Delta E \approx -30 \frac{\sqrt{E}}{\lambda} \qquad (8)$$

Where

ΔE = error in peak volts

E = applied peak voltage

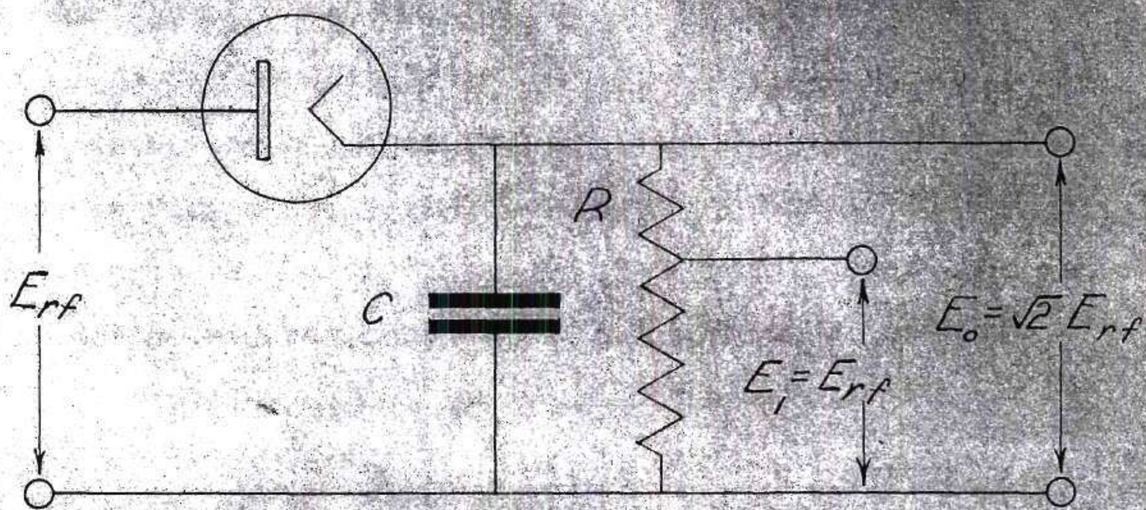
λ = operating wavelength in centimeters

The input series resonant frequency of the 955 is lowered by the leads employed to connect it to the potential under measurement. Care must be exercised in using the diode so that there will not be a larger resonance error at lower frequencies than indicated by the correction formula. The correction formulas indicate the degree of departure of the actual voltage reading made at ultra-high frequencies as compared to the calibration at a frequency of 60 cycles.

Fig.10 is the basic diagram of the diode peak voltmeter. If R is large as compared to the diode resistance R_d, and if C has a negligible reactance at the frequency of the applied voltage, the d-c voltage developed across R is essentially equal to the peak value of the applied voltage. For large ratios of load to diode resistance, the voltage developed across the condenser may be taken as the peak value of the input voltage with very little error.

The input resistance of the diode voltmeter of Fig. 10 at low and medium frequencies is approximately 1/2 R. At high frequencies, the effective input resistance is

Fig.10



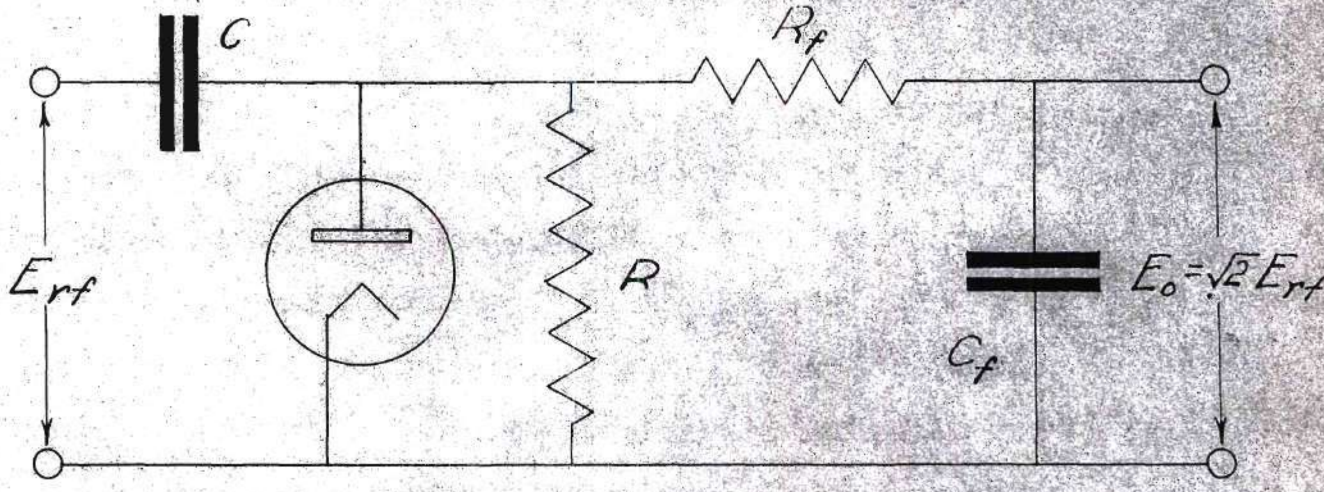


Fig.11

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dependent mainly upon dielectric losses in the diode envelope, socket, and connecting terminals.

Due to the fact that a comparatively high current flows through the diode during a small portion of the cycle of the input signal, the diode will not indicate the true voltage when the voltage source has a high internal impedance. The internal resistance of the diode voltmeter from this viewpoint may be determined by connecting the diode in series with a high variable resistance to a low-impedance a-c voltage source. The reading of the diode with the resistance equal to zero is first noted, then the resistance is increased until the diode reading is reduced to one-half of its former value. The internal resistance of the diode from the voltage-reduction standpoint is the same as the resistance employed to halve the diode reading.

The diode voltmeter shown in Fig.10 indicates the peak value of the total voltage applied to its input terminals. When it is desired to measure the peak value of an a-c voltage in the presence of a d-c voltage, it becomes necessary to filter out the d-c component. This may be done readily by employing the diode voltmeter of Fig.11. Since there is a condenser in its input lead, this voltmeter indicates the peak value of the a-c input voltage, and the reading is unaffected by any d-c voltage present in the source.

However, since the total a-c voltage appears across the diode, it is necessary to employ a radio-frequency filter to remove the a-c voltage from its output terminals. An advantage of this diode voltmeter connection is that the stray potential developed by the diode, in the absence of any input voltage, appears continuously across its output terminals. It is evident, however, that the full radio-frequency voltage is applied across both R and R_f, so that this voltmeter can be expected to have considerable radio-frequency power losses in the material surrounding these resistors.

Since there is an appreciable capacitance between the condenser C and the metal shield surrounding the diode probe, it is essential that this condenser be encased in a material having an extremely low power factor to reduce losses from this source. This stray capacitance is shunted across the input of the diode, thus increasing the input capacitance of the voltmeter. For low-frequency measurements, C must have a high capacity in order to insure that its reactance will be low. This will require the use of a rather bulky probe construction.

The diode voltmeter of Fig. 10 will not give a reading unless the voltage source provides a d-c path across the voltmeter input terminals. It is evident that the stray potential developed by the diode appears across its output terminals only when a voltage measurement is being made, or when a d-c path is completed across its input terminals. An advantage of this diode voltmeter is that it has an extremely low input capacitance determined entirely by the plate-cathode capacitance of the tube plus the shunt capacitance of the probe terminals. The diode voltmeter of Fig. 10 lends itself admirably to a compact probe construction, since the condenser C may consist of a high-quality mica condenser mounted in the probe to provide a low-impedance path for high-frequency currents, while a larger condenser, located near the indicating instruments, may be connected in parallel with it to provide a low-impedance path for the low-frequency currents.

If the voltage measured contains even harmonics in such phase position that the positive and the negative half cycles have different peak values, a half-wave peak diode voltmeter is subject to a large turnover error. Although the diode will not indicate accurately the value of a fundamental voltage containing harmonics, it is essential that the voltmeter give the same voltage reading when its input terminals are reversed. A full-wave diode rectifier will give readings free from a turnover error.

A 6H6 twin-diode tube, or two RCA-955's, connected as a voltage-doubler rectifier operates successfully at radio frequencies. The diode voltage doublers are particularly convenient for use in vacuum-tube voltmeters in which application they are sensitive full-wave peak voltmeters free from a turnover error.

Fig. 12 shows the conventional voltage-doubler rectifier circuit in which the series-connected condensers C_1

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Fig. 12

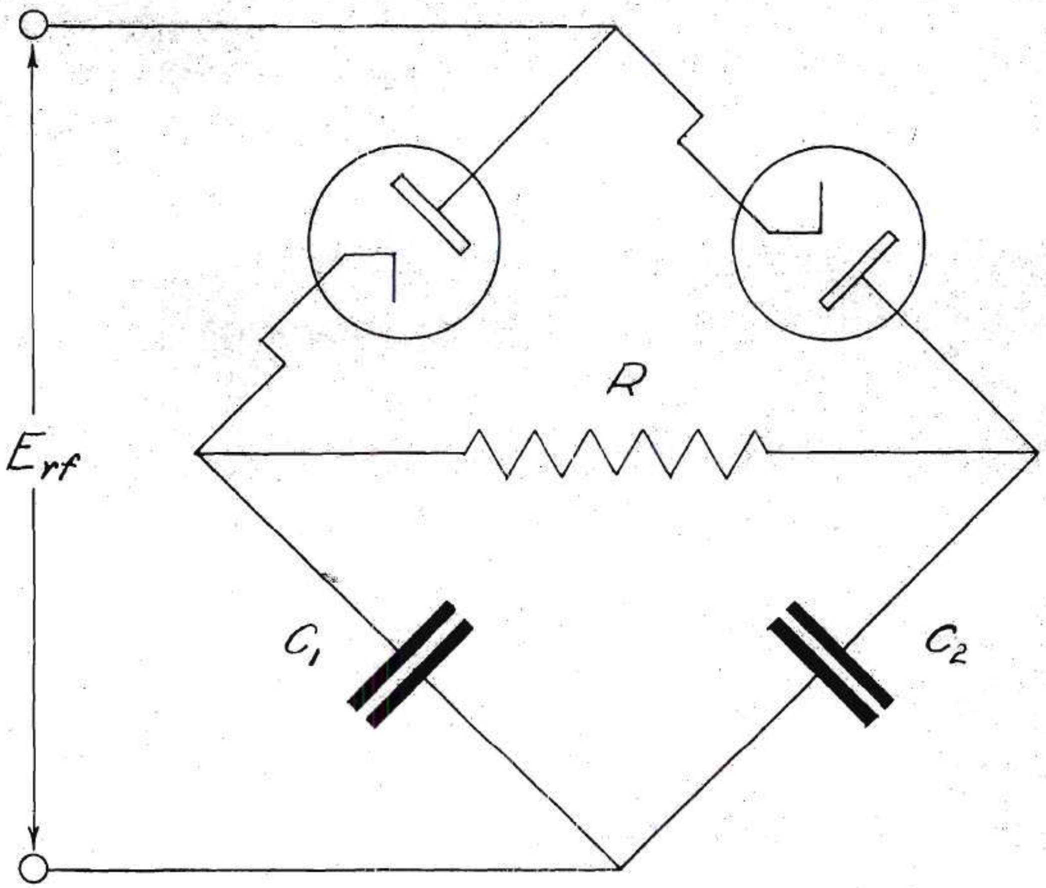
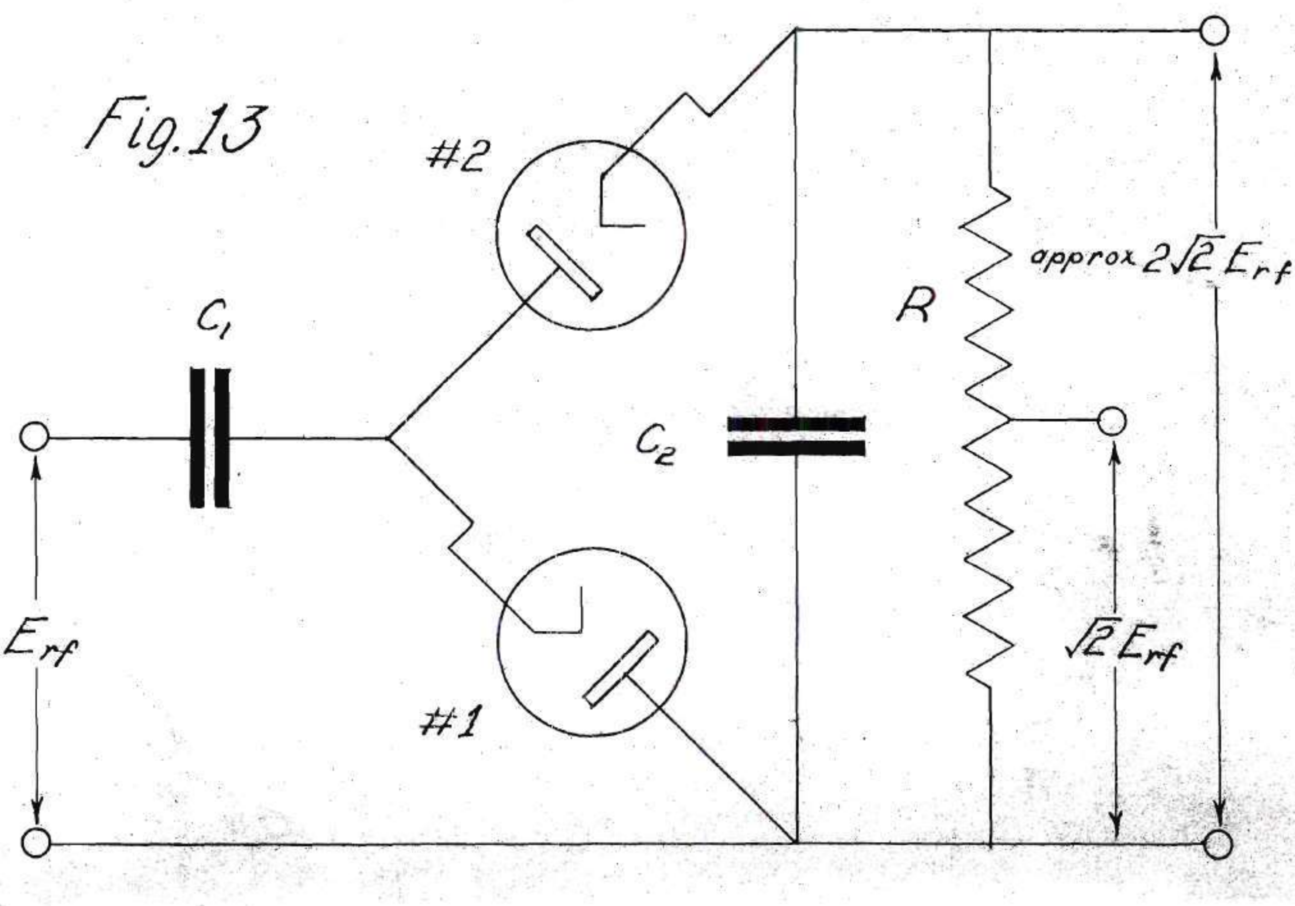


Fig. 13



and C_2 are charged in succession on alternate half cycles of the applied voltage E_{rf}. If the condensers have a high capacitance and R has a high resistance, the d-c voltage developed across R is very nearly twice the peak a-c input voltage. The lowest ripple frequency present in the output is twice the input frequency. It is apparent that both terminals of the load resistance are at ground radio-frequency potential, therefore, the stray shield-to-ground capacitance of the d-c voltmeter used to measure the potential across R will be in shunt with either C_1 or C_2. The cathode-to-heater-to-cathode capacitance of the diodes is shunted across the input of the voltage doubler.

Fig. 13 shows a lesser-known voltage doubler rectifier circuit in which C_1 is charged to E_{rf} peak during the half cycle that diode No. 1 conducts the current, and then C_1, in series with the line, charges condenser C_2 to twice E_{rf} peak on the next half cycle, when diode No. 2 conducts current. The lowest ripple frequency present in the output is the same as the input frequency. In this circuit, the cathode-to-heater-to-cathode capacitance of the diodes is shunted across one of the diodes.

A decided advantage in the use of either voltage doubler in a voltmeter for a-c measurements is that the condensers break the d-c path in the input circuit so that the instrument reads only the a-c component of the input voltage, should it contain a d-c component. The doubler of Fig. 13 possesses an advantage over the doubler of Fig. 12 in that there is a common input and output terminal, which permits the use of a common ground point.

When it is necessary to make measurements on balanced push-pull circuits, or on parallel-wire transmission or telephone lines, a balanced voltmeter is desirable. Two 6H6's connected in a bridge rectifier arrangement employing a resistance-capacitance load circuit, with one of the output terminals grounded, form a balanced peak voltmeter with a reasonably low input capacitance. If strong even harmonics are present, or if there is an unbalance to ground, two of the diodes will be inoperative, since the other two diodes will charge the output condenser to a voltage high enough to keep the first two diodes at cut-off. The voltage indicated will then be the voltage from one line to ground.

THE EMPIRICAL CALIBRATION OF DIODE VOLTMETERS

When measurements using pure sinusoidal voltages are to be made, the voltmeter of Fig. 10 can be accurately calibrated to give the effective value of the input voltage in the following manner: A known a-c or r-f voltage from a low-impedance source is fed to the input terminals of the diode voltmeter. Then the resistance R is tapped at a point which will make the d-c voltage E_1 exactly equal to the effective value of E_{rf}. The voltmeter may be calibrated at radio-frequencies in this manner by comparison with a thermo-couple voltmeter.

In a similar manner, the voltmeter of Fig. 13 may be adjusted so that the output d-c voltage is exactly equal to either the peak value, or the effective value, of the input voltage.

Since the d-c voltmeter used to measure the output voltage of the diode voltmeters reads the difference between the initial and the final voltage across its terminals, the stray potential developed by the diodes does not affect the reading.

When high values of load resistance are employed, a linear relationship exists between the peak input voltage and the output d-c voltage of the diode voltmeter.

THE DESIGN OF THE DIODE VOLTMETER

No single diode voltmeter circuit arrangement will permit all of the different kinds of voltage measurements encountered in communications work. For, example, it is often necessary to make measurements of voltage across circuits which have one point grounded, across ungrounded circuits, across circuits with the mid-point grounded, etc. In order to insure a maximum utility and flexibility, a plug-in arrangement is employed so that various diode voltmeters may be plugged into the direct-current voltmeter.

The diode voltmeter preferred by the writer for general measurements employs the circuit of Fig. 10. It consists of an RCA-955, a high-quality 0.02 uf. mica condenser and a 100 megohm resistor mounted in a brass case at the end of a flexible "goose-neck". A larger condenser and a lower resistance can be conveniently plugged into the d-c voltmeter in parallel with the R-C combination in the probe, when it is desirable to do so. The probe input terminals are mounted on a polystyrene strip to insure low radio-frequency losses.

RESULTS

The input capacitance of the diode voltmeter measured by the resonance method at a frequency of 600 kilocycles is 4.35 micromicrofarads.

At a frequency of 600 kilocycles, the diode voltmeter read 1.8% low as compared to the reading of a calibrated thermocouple. This error is, in part, augmented by the fact that the voltage measurement was made across a standard variable condenser in a high-Q parallel resonant circuit, which has a high resonant impedance.

The writer had no means at his disposal to measure the resonant frequency of the input loop of the diode voltmeter. Comparisons between this diode voltmeter and similar diode voltmeters constructed by the General Radio Company and L. S. Nergaard indicate that the resonant frequency of the input loop is not less than 300 megacycles.

Direct voltages measured directly by the slide-back voltmeter and then measured with a 10 megohm resistance in series with the input terminals and the unknown voltage give identical readings. The terminal voltage of Mallory bias cells is conveniently measured with the slide-back voltmeter.

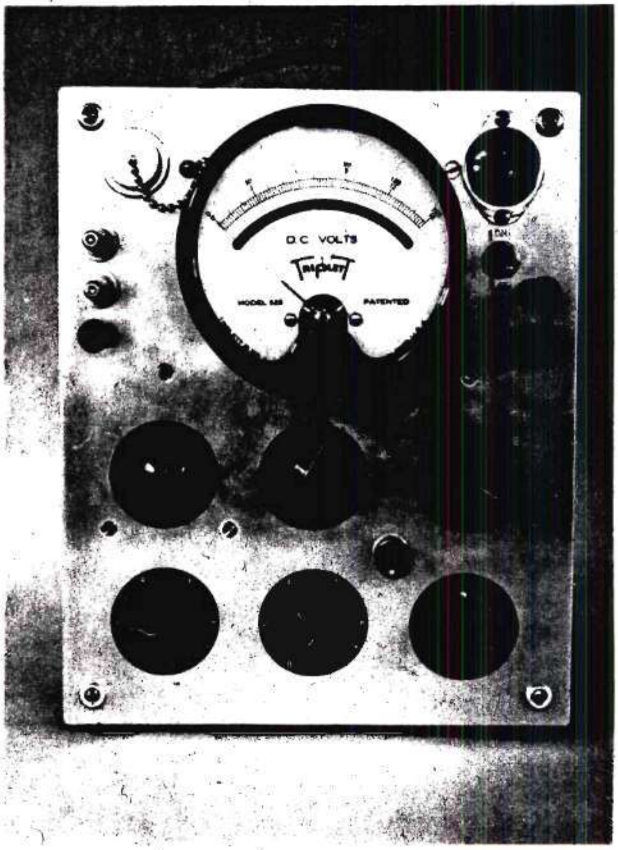
CONCLUSIONS

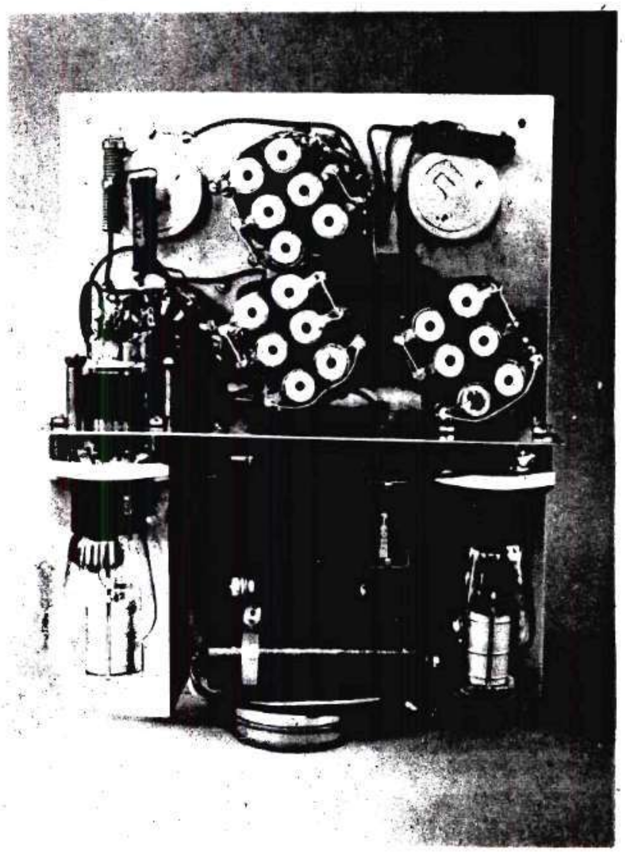
Photographs of the completed voltmeter appear in Fig. 14. A three-pole triple position switch is employed to switch from the slide-back connection to the direct-reading degenerative connection. One position of the switch is left free and ample room is provided in the voltmeter for future changes, or additions, which may prove desirable after a period of use.

Although this particular d-c slide-back voltmeter is arranged to read with positive potentials applied to the grid, this type of circuit works quite satisfactorily, over a limited range of input voltages, with negative potentials applied to the grid. Cursory tests indicate that tetrodes or pentodes work satisfactorily in the slide-back voltmeter.

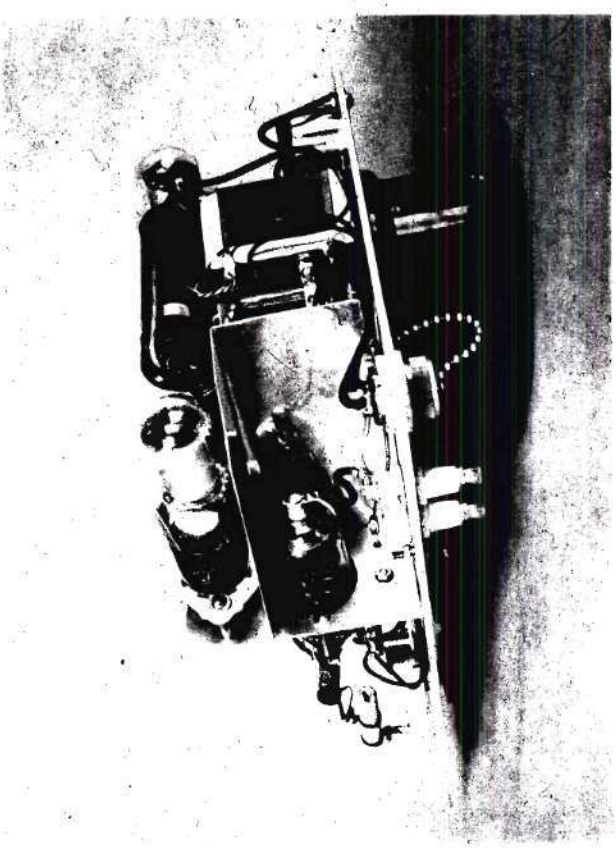
The utility of a diode voltmeter, used with a shunted condenser, as a radio frequency ammeter of high accuracy cannot be over emphasized. Low-current thermocouples often have an undesirably high resistance. In such cases, the diode-condenser ammeter may be advantageously employed.

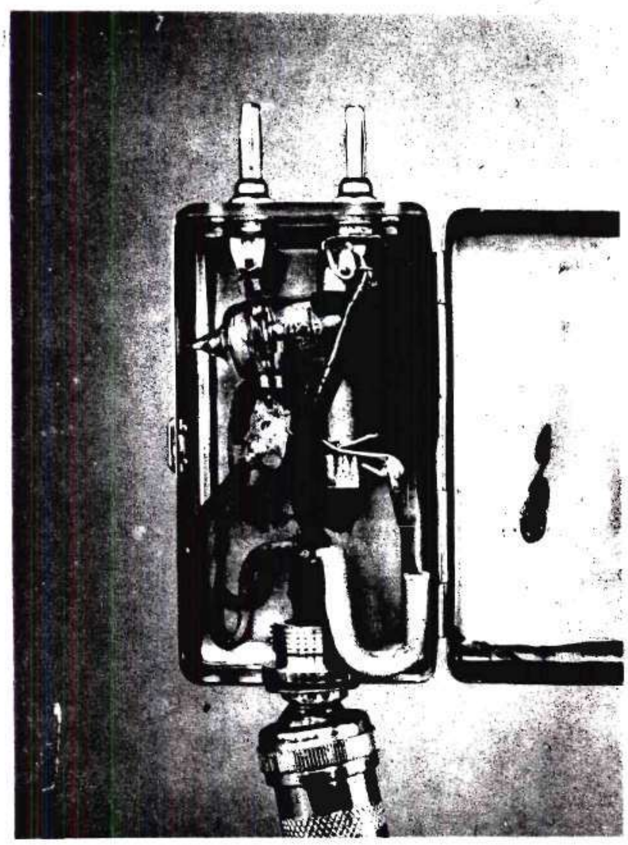
All of the desirable features of a vacuum-tube voltmeter as outlined in the introduction to this paper are fully met by this vacuum-tube voltmeter. The direct current slide-back voltmeter is completely self-calibrated upon construction. If the diode voltmeter is empirically calibrated in the manner described by the writer, it is rendered as accurate as the standard employed to calibrate it. The methods employed to calibrate the voltmeter preclude any possibility





D-C Voltmeter Fig. 14 Rear View





6F5GT Shielded Compartment

Diode Voltmeter

of determining any error greater than the sum of the errors in the individual parts comprising the voltmeter. The total per cent error is, therefore, under the direct control of the designer.

In conclusion, it is well to point out that an accurate vacuum-tube voltmeter in the hands of an individual who does not appreciate fully the intricacy of radio and electronics measurements, is not a fool-proof instrument. This voltmeter, judiciously handled, should open new fields of investigation to the trained communications engineer.

BIBLIOGRAPHY

Vacuum-tube Voltmeters in General

Reich, H. J.: Theory and Applications of Electron Tubes, Chapter 15.

Terman, F. E.: Measurements in Radio Engineering, Chapter 1.

Brown, H. A.: Radio-Frequency Electrical Measurements, Chapter 6.

General Radio Experimenter, May, 1937.

Wolf, I.: Proc. I.R.E., Vol. 19, p. 647, 1931.

Aiken, C. B; Birdsall, L. C.: Trans. A.I.E.E., Vol. 57, p. 171.

Contact Potential

Bowie, R. M.: Proc. I.R.E.,Vol. 24, p. 1501, 1936.

Diode Voltmeters

Ferris, W. R.: Proc. I.R.E., Vol.24, p. 82, 1936.

Nergaard, L. S.: Proc. I.R.E., Vol. 24, p. 1207, 1936.

Wheeler, H. A.: Proc. I.R.E., Vol. 26, p. 745, 1938.

Aiken, C. B.: Proc. I.R.E., Vol.26, p. 859, 1938.

Thompson, B. J.; Rose, G. M.: Proc. I.R.E., Vol. 21, p. 1707, 1933.

Nergaard, L. S.: RCA Review, Vol. 3, p. 156, 1938

Thompson, B. J.: RCA Review, Vol. 3, p. 146, 1938.